

Spin-Alignment and Quasi-Molecular Resonance in Heavy-Ion Collision

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Abstract

*Fragment-fragment- γ triple coincidence measurements of the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at $E_{\text{c.m.}} = 55.8$ MeV, carefully chosen to populate a well known quasi-molecular resonance in ^{56}Ni , have been performed at the VIVITRON tandem facility by using the Eurogam Phase II γ -ray spectrometer. In the $^{28}\text{Si} + ^{28}\text{Si}$ reaction, the resonant behavior of the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel is clearly observed by the present fragment-fragment coincidence data. The more unexpected result is the spin disalignment of the $^{28}\text{Si} + ^{28}\text{Si}$ resonance. This has been demonstrated first by the measured angular distributions of the elastic 0^+ , inelastic 2^+ and mutual excitation channels $2^+ - 2^+$, which are dominated by a unique and pure partial wave with $L = 38 \hbar$, and has been confirmed by measuring their particle- γ angular correlations with Eurogam Phase II. The spin disalignment supports new molecular model predictions, in which the observed resonance would correspond to the "Butterfly mode". A discussion concerning the *spin alignment and spin disalignment* for different systems : $^{12}\text{C} + ^{12}\text{C}$, $^{24}\text{Mg} + ^{24}\text{Mg}$ and $^{28}\text{Si} + ^{28}\text{Si}$ will be given.*

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I. Introduction

One of the most intriguing results in the study of heavy-ion resonances has been the observation of the pronounced, narrow and well isolated quasi-molecular resonances in the elastic and inelastic scattering of medium mass nuclei. The first observation of such resonant structures in systems around the mass $A = 50$ region was reported by Betts et al. [1] in $^{28}\text{Si} + ^{28}\text{Si}$. Even more pronounced resonance structures were later reported in $^{24}\text{Mg} + ^{24}\text{Mg}$ [2] system, while other symmetric systems such as $^{32}\text{S} + ^{32}\text{S}$ [3] and $^{40}\text{Ca} + ^{40}\text{Ca}$ [6] do not show such behavior. Resonance structures were also found in the asymmetric system $^{24}\text{Mg} + ^{28}\text{Si}$ [4]. The appearance of narrow resonances in medium-heavy systems may open up the possibility for studying nuclear structure at high spin in the continuum of the complex dinuclear system. The excitation functions for elastic and inelastic scattering for several low-lying excitations in $^{28}\text{Si} + ^{28}\text{Si}$ and $^{24}\text{Mg} + ^{24}\text{Mg}$ are shown in Fig.1 (figures taken from [1,2]). Perhaps the most intriguing aspect of these excitation functions is the narrow width structures which are observed to be very highly correlated.

For a better understanding of the nature of these resonances it is important to know their detailed properties. Most important is the determination of their spins. One of the explanations suggested for the nature of these resonances is that they are associated with quasi-stable configurations with extreme deformation. This interpretation is supported by Nilsson-Strutinsky model calculations. In this model the structure of the compound nucleus at large deformation and high angular momenta has been considered. Calculations of the potential energy surfaces for nuclei such as ^{56}Ni and ^{48}Cr using the Nilsson-Strutinsky prescription show significant secondary minima ($\beta = 0.9$) at extremely large prolate deformations. An example of such a potential energy surface is shown in Fig.2 (figure taken from [5,6]), for the nuclei ^{56}Ni at spin $I = 40$ and ^{48}Cr at spin $I = 36$ respectively.

In this paper, we present experimental results for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction using very powerful coincidence (fragment-fragment-gamma : Eurogam Phase II with ancillary detectors) techniques. These results supply, for the first time in a heavy-ion resonance, evidence

for a spin disalignment between the binary fragments spins and the total angular momentum. This result which will be interpreted in the framework of a molecular model by a "Butterfly motion". The search for highly deformed bands in the ^{28}Si nucleus produced in the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at a resonance energy $E_{\text{lab}} = 111.6$ MeV is presented. A discussion concerning the *spin alignment and disalignment* for the following systems $^{12}\text{C} + ^{12}\text{C}$, $^{24}\text{Mg} + ^{24}\text{Mg}$ and $^{28}\text{Si} + ^{28}\text{Si}$ will be given.

II. Experimental Techniques

"Eurogam Phase II with Ancillary Detectors"

The experiment $^{28}\text{Si} + ^{28}\text{Si}$ was performed at the IReS Strasbourg VIVITRON tandem facility with a ^{28}Si beam at the bombarding energy $E_{\text{lab}}(^{28}\text{Si}) = 111.6$ MeV, carefully chosen to populate the well known 38^+ resonance [7]. The ^{28}Si beam was used to bombard a $25 \mu\text{g}/\text{cm}^2$ thick ^{28}Si target. The thickness of the target corresponds to an energy loss of 130 keV, which is smaller than the resonance width ($\Gamma_{\text{c.m.}} \approx 150$ keV). The experiment has been carried out in a triple coincidence mode (fragment-fragment- γ). The fission fragments were detected in two pairs of large-area position-sensitive Si(surface-barrier) detectors (PSD) placed on either side of the beam axis and their masses were determined by using standard kinematic coincidence techniques [8]. The opening angle of the PSD's covered in the laboratory the angular range 22° to 73° in the horizontal plane. The γ -rays were detected in the Eurogam Phase II multi-detector array [9], which consists of 54 Compton-suppressed germanium (Ge) detectors, 30 tapered coaxial Ge detectors from Eurogam Phase I located in the forward and backward hemispheres, and 24 clover detectors installed at $\approx 90^\circ$ relative to the beam axis. The number of the Ge crystals at each angle with respect to the beam direction is (5, 22°), (10, 46°), (24, 71°), (24, 80°), (24, 100°), (24, 109°) (10, 134°) and (5, 158°). Energy and relative efficiency calibrations of Eurogam Phase II were obtained with standard γ -ray sources and an AmBe source for the higher energy γ -ray region [9,10,11]. The detectors associated with the experiment $^{28}\text{Si} + ^{28}\text{Si}$ (fragment-fragment- γ) are shown in Fig.3. The

γ -rays emitted by excited fragments are detected by the Ge detectors of Eurogam Phase II. Doppler-shift corrections were applied to the γ -ray data on an event-by-event basis using measured velocities and angles of the detected fragments.

III. Experimental Results of $^{28}\text{Si} + ^{28}\text{Si}$ Reaction

Fig.4 shows the two-dimensional energy spectrum E_3 - E_4 of the fragments in coincidence with one pair of position-sensitive detectors. Three regions, noted 1, 2 and 3, can be distinguished in the figure. The region 1 corresponds to the binary products of the $^{28}\text{Si} + ^{28}\text{Si}$ reaction. In this region the spectrum shows well structured distributions indicating that the bombarding energy corresponds well to the resonance energy. The region 2 arises from the reaction products of the ^{28}Si with heavy contaminants, and region 3 corresponds to the light charged particle (p , α) coincidences arising from the fusion-evaporation of the ^{56}Ni compound system. The identification of different exit channels corresponding to region 1 has been obtained by using mass spectra (as shown in Fig.5) constructed by standard binary kinematic relations [9].

Fig.5 shows that the region 1 is formed by two kinds of reaction. The first (Fig.5.A) corresponds to reaction products of $^{28}\text{Si} + ^{28}\text{Si}$ at resonance energy $E_{\text{lab}} = 111.6$ MeV and shows that the reaction is dominated by the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel. This is due to the fact that the PSD's locations have been optimised to study this exit-channel. The second reaction (Fig.5.B) arises from the reaction ^{28}Si on the ^{16}O target contaminant.

In order to understand better the nature of the quasi-molecular resonances it is important to know their detailed *spin* properties. For this purpose we will focus our analysis on the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel.

A. Fragment-Fragment Coincidence Measurements

“Observation of Spin Disalignment ”

By setting gates with the conditions $M_T = 56$ and $M_3 = 28$ in the mass spectra, we have selected the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel [9]. This has permitted us to construct the excitation energy spectra (E_X) defined by the following expression :

$$E_X = Q_{gg} - Q^* = Q_{gg} + E_{\text{lab}} - (E_3 + E_4) \quad (1)$$

where Q_{gg} is the reaction Q -value. E_3 and E_4 are the energies of the two fragments detected in coincidence.

Fig.6 shows the gated two-dimensional spectrum of the ejectile energy E_3 as a function of the excitation energy E_X for the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel. The vertical band corresponds to different excited states in the two ^{28}Si fragments, whereas the regular pattern of yields are due to strongly structured angular distributions. In order to investigate the resonance effects, we will extract the angular distributions from the projections on the E_X axis with excitation energy gates around $E_X \approx 0, 1.7 \text{ MeV}, 4 \text{ MeV}, 6 \text{ MeV}$ and 10 MeV corresponding to the different states of the two ^{28}Si fragments. This method, which allows us to extract the angular distributions at the different excitation energies, will permit us to determine the dominant orbital angular momentum characterizing the distributions and to distinguish between resonance and fission processes.

The angular distributions (AD) for identical particle exit-channel $^{28}\text{Si} + ^{28}\text{Si}$ at different excitation energies are displayed in Fig.7. We can distinguish two trends in the AD behavior :

1 - At the low-lying states $E_X \leq 4 \text{ MeV}$:

The $^{28}\text{Si}(^{28}\text{Si}, ^{28}\text{Si})^{28}\text{Si}$ identical particle exit-channel at $E_{\text{lab}} = 111.6 \text{ MeV}$ was found to have at backward angles (between $70^\circ \leq \theta_{c.m.} \leq 110^\circ$) strongly oscillatory angular distributions for the elastic, inelastic, and mutual excitation channels as shown in Fig.7. The present large-angle high-quality data, with good position resolution and high statistics, are

well described by the curves of Fig.7 as calculated by $[P_L(\cos \theta_{c.m.})]^2$ shapes with $L = 38 \hbar$ in perfect agreement in the elastic channel with the previous data of Betts et al. [7]. The fact that the measured angular distributions in the elastic, inelastic, and mutual excitation channels correspond to shapes characterized by the same single Legendre polynomial squared means that the resonant behavior is dominated by a unique and pure partial wave associated with the angular momentum value $L = 38 \hbar$. This value can finally be considered as the spin of the well defined and isolated quasi-molecular resonance.

Knowing that the total angular momentum $\vec{J} = \vec{L} + \vec{I}$ is conserved and that the angular momentum $L = 38 \hbar$ is dominant in these three resonant channels implies that the projection of the spin along the direction perpendicular to the reaction plane is $m = 0$. This is the signature of the disalignment between the relative angular momentum \vec{L} and total spin \vec{I} .

This signature of spin disalignment will be verified in the following by fragment-fragment-gamma correlation measurements for the two low-energy inelastic excitations using the Eurym Phase II multi-detector array.

2 - At the high excitation states $E_X \geq 6 \text{ MeV}$:

The identification of the excited states $(3_1^-, 0_1^+)$, $(4_1^+, 2_1^+)$ and $(4_1^+, 4_1^+)$ as shown in Fig.7 at high excitation energy $E_X \geq 6 \text{ MeV}$ has been obtained by using γ -ray coincident data. The AD for mutual excited states $(3_1^-, 0_1^+)$ and $(4_1^+, 2_1^+)$ at the excitation energy $E_X \approx 6 \text{ MeV}$ are not so strongly structured as compared to the low-lying states and it is difficult to fit them by the Legendre polynomial squared. Therefore the AD for mutual excited states $(4_1^+, 4_1^+)$ has a shape comparable to a $1/\sin \theta_{c.m.}$ behavior and we can consider the two ^{28}Si fragments as being emitted from a fully relaxed process such as *fusion-fission*.

In general the angular distributions show that the low-lying states are characterised by the resonance phenomena and, for the first time, by *spin disalignment*. The fission process is believed to dominate the distribution at high excitation energy $E_X \geq 6 \text{ MeV}$.

B. Fragment-Fragment-Gamma Coincidence Measurements

“Confirmation of Spin Disalignment ”

In order to understand this disalignment we will focus our analysis on the fragment-fragment- γ coincidence data of the $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel [9,10,11]. Spin disalignment estimates of the low-lying excitation states (single inelastic 2_1^+ and mutual inelastic ($2_1^+, 2_1^+$) exit-channels) have been deduced by measuring their particle- γ angular correlations with Eurogam Phase II.

In Fig.9 three quantization axes have been defined as follows : a) corresponds to the beam axis, b) axis normal to the scattering plane, and c) axis perpendicular to the a) and b) axes. The fragment detectors are placed symmetrically with respect to the beam axis and their centers are located at angles $\theta_{\text{lab.}} \simeq \pm 45^\circ$, then the c) axis can be approximatively considered as the molecular axis parallel to the relative vector between the two centers of the out-going binary fragments. In Fig.8 the results of the γ -ray angular correlations for the mutual excitation exit-channel are shown. It is interesting to note that almost identical results have been also obtained for the single excitation exit-channel. The minima observed in a) and b) at 90° imply that the intrinsic spin vectors of the 2^+ states lie in the reaction plane and are perpendicular to the orbital angular momentum. So the value of the angular momentum remains close to $L = 38 \hbar$ for the two exit channels, in agreement with Fig.7. The maximum around 90° in c) suggests that the ^{28}Si spin vectors are parallel to the fragment directions with opposite directions. Such disalignment of the fragment spins are, of course, not usual in deep inelastic processes [12], but a very long life-time of the resonance might allow large microscopic fluctuations. In the present experiment the feeding of the ^{28}Si states are also measured. The study of the feeding of the bands of ^{28}Si , has revealed that the ^{28}Si is dominated by *oblate* deformation [9,10,11].

Recently A.H. Wuosmaa et al. [13] have observed that the prolate-prolate system $^{24}\text{Mg} + ^{24}\text{Mg}$ is characterised by spin alignment and this is in contrast with our results in the oblate-oblate system $^{28}\text{Si} + ^{28}\text{Si}$. In the following section we will attempt to ex-

plain spin disalignment in the oblate-oblate system $^{28}\text{Si} + ^{28}\text{Si}$ and spin alignment in the prolate-prolate system $^{24}\text{Mg} + ^{24}\text{Mg}$ by using a new molecular model.

C. Molecular Model

“Interpretation of Spin Disalignment : Butterfly Motion”

Quasi-molecular resonances in heavy-ion scattering of $^{28}\text{Si} + ^{28}\text{Si}$ and $^{24}\text{Mg} + ^{24}\text{Mg}$ are examined in the framework of a new molecular model. The general ideas of the molecular model are based on the following considerations : the occurrence of elongated but stable dinuclear configurations and their characteristic normal-mode of motions at equilibrium is proposed to be the origin of the observed resonant structures. The problem is ”how to find and how to describe these motions?”. For this purpose, we define a rotating molecular frame of the dinuclear system, and consider collective motions of the intrinsic states [9,14,15,16,17].

A stable configuration of the $^{24}\text{Mg} + ^{24}\text{Mg}$ scattering is found to be a *pole-pole* (P-P) configuration, due to the prolate shape of the ^{24}Mg interacting nuclei. Around the equilibrium various dynamical modes which may appear could be responsible for the observed narrow resonances [13]. In an oblate-oblate system $^{28}\text{Si} + ^{28}\text{Si}$ (the ^{28}Si nucleus has an oblate shape [9,10,11]) with high spins such as 38h, an equator-equator (E-E) touching configuration is favored. Hence it is interesting to investigate molecular modes around such a new type of equilibrium. In Fig.10, an oblate-oblate configuration is displayed, where we have introduced a rotating molecular frame, the z' -axis of which is parallel to the relative vector of the two interacting nuclei. For the sake of simplicity, we consider the system of two identical deformed nuclei with a constant deformation and axial symmetry, and then we have seven degrees of freedom. Three of them are from the relative vector $\mathbf{R} = (R, \theta_1, \theta_2)$. Collective degrees of freedom of deformed nuclei are the orientations of the symmetry axes, which are described by the Euler angles (α_1, β_1) and (α_2, β_2) . α_1 and α_2 are combined into $\theta_3 = (\alpha_1 + \alpha_2)/2$ and $\alpha = (\alpha_1 - \alpha_2)/2$. Thus we have $(q_i) = (\theta_1, \theta_2, \theta_3, R, \alpha, \beta_1, \beta_2)$, where θ_i 's are the Euler angles of the molecular frame with four other internal variables. Consis-

tent with the coordinate system, we introduce rotation-vibration type wave functions as the basis,

$$\Psi \sim D_{MK}^J(\theta_i)\chi_K(R, \alpha, \beta_1, \beta_2). \quad (2)$$

By solving the internal motions for $\chi_K(R, \alpha, \beta_1, \beta_2)$, *butterfly and anti-butterfly* vibrational modes, and K -and twisting-rotational modes (associated variables θ_3 and α , and quantum numbers K and ν , respectively) are obtained (Details are given in Ref. [9,16,17]). Fig.11 and 12 display recent theoretical analyses for $^{28}\text{Si} + ^{28}\text{Si}$ and $^{24}\text{Mg} + ^{24}\text{Mg}$ in the excited states $(2_1^+, 2_1^+)$ for the normal-mode motions by the molecular model.

For $^{28}\text{Si} + ^{28}\text{Si}$: Fig.11 shows (see panel B) that there is an extreme of the probabilities for channel spin of $I = 0$ for Butterfly motion. This is in good agreement with the experimental angular distribution with $L = J$ in Fig.7. Furthermore, very recently, the molecular model is developed [14] to include the K -mixing, and a tilting mode is obtained. The results exhibit strong concentration in "m = 0" states [14], which may be in good agreement with the experimental γ -ray distribution. Work is in progress for a reasonable comparison between the data and the calculated results. It seems anyway that in the $^{28}\text{Si} + ^{28}\text{Si}$ system (oblate-oblate), the spin disalignment could result from a Butterfly motion and tilting mode [9,10,11].

For $^{24}\text{Mg} + ^{24}\text{Mg}$: Fig.12 shows that for the $^{24}\text{Mg} + ^{24}\text{Mg}$ system (prolate-prolate) the different vibrational modes result in channel spin probabilities which are more equal. In this case the Butterfly motion is not anymore the dominant mode.

As a consequence the qualitative differences between $^{28}\text{Si} + ^{28}\text{Si}$ and $^{24}\text{Mg} + ^{24}\text{Mg}$ in the $(I_1, I_2) = (2_1^+, 2_1^+)$ channel are clearly obtained.

IV. Discussion and Comparison between Different Systems

“ $^{12}\text{C} + ^{12}\text{C}$, $^{24}\text{Mg} + ^{24}\text{Mg}$ and $^{28}\text{Si} + ^{28}\text{Si}$ ”

The first observation of the correlated spin orientation (alignment spin) has been in $^{12}\text{C} + ^{12}\text{C}$ quasi-molecular resonances in 1985 [18]. In this case the correlation between the

spin orientations of the two $^{12}\text{C}(2^+)$ nuclei in mutual inelastic $^{12}\text{C} + ^{12}\text{C}$ scattering has been deduced from the directional correlations of the particle-coincident γ -ray measured with the Heidelberg crystal-ball detector. Resonances in the cross section are found to be nearly uniquely associated with the mutually aligned component. The strong resonance structure as well as the characteristic behavior of the angular distributions of this reaction component are suggestive of the formation of a rotating complex in the sticking configuration. Because of the deformed shape of ^{12}C (oblate), the sticking condition, which is a well-known classical characteristic of deep-inelastic collisions in heavier systems [19], becomes relevant for the quantum mechanical phenomenon of $^{12}\text{C} + ^{12}\text{C}$ resonances.

Two years after the observation of the spin alignment in $^{12}\text{C} + ^{12}\text{C}$ molecular resonances, A. Wuosmaa and collaborators [13] have measured the single and correlated magnetic-substate population parameters for 2^+ and 2^+-2^+ excitations in $^{24}\text{Mg} + ^{24}\text{Mg}$ (prolate-prolate system) in the region of two strong resonances observed in inelastic scattering. They have performed their γ -ray angular correlation and angular-distribution measurements using the Oak Ridge Spin Spectrometer. This device is a multidetector NaI spectrometer comprised of 70 NaI γ -ray detectors. These data have provided spectroscopic information relatively uncontaminated by nonresonant amplitudes, and allow spin assignment of $J^\pi = 36^+$ for two resonances $E_{\text{c.m.}} = 45.70$ and 46.65 MeV. The angular correlation data for the mutual 2^+ inelastic scattering channel suggest a dominant decay ℓ value of $\ell = 34 \hbar$ for both resonances. Correlated spin alignment data for this channel confirm the expectations for the relationship between angular momentum coupling and spin alignment for these resonances. The relatively high spin values suggest a resonance configuration in which the two ^{24}Mg nuclei interact pole-to-pole, allowing the system to sustain a large amount of angular momentum. This results is well corroborated by the molecular model [17].

In the present experiment $^{28}\text{Si} + ^{28}\text{Si}$ (oblate-oblate system), performed at the resonance energy $E_{\text{c.m.}} = 55.8$ MeV high-resolution fragment-fragment- γ data have been collected with the Eurogam Phase II multi-detector array. It is to our knowledge the first time that the disalignment spin has been observed in a heavy ion reaction. This has been primarily shown

in the measured angular distributions of the elastic, inelastic 2^+ , and mutual excitation channels 2^+-2^+ , which are dominated by a unique and pure partial wave with $L = 38 \hbar$, and has been confirmed by measuring their particle- γ angular correlations with Eurogam Phase II. Within the molecular model the spin disalignment is taken to suggest a dominance of the Butterfly mode in the vibrational motion of the observed resonance. Therefore a stable configuration is inferred to be an elongated one, namely an equator-to-equator touching configuration.

The comparison between the three symmetric systems $^{12}\text{C} + ^{12}\text{C}$, $^{24}\text{Mg} + ^{24}\text{Mg}$ and $^{28}\text{Si} + ^{28}\text{Si}$ shows an interesting contrast in the spin orientation at resonance energies. The results indicate that $^{28}\text{Si} + ^{28}\text{Si}$ (oblate-oblate system) is characterised by spin disalignment in contrast to the observed spin alignment for $^{12}\text{C} + ^{12}\text{C}$ system (oblate-oblate) and $^{24}\text{Mg} + ^{24}\text{Mg}$ system (prolate-prolate). The molecular model calculations explain the spin disalignment in the oblate-oblate $^{28}\text{Si} + ^{28}\text{Si}$ system by a Butterfly motion. Now the question arises, "why is the orientation of spin in the two oblate-oblate systems $^{28}\text{Si} + ^{28}\text{Si}$ and $^{12}\text{C} + ^{12}\text{C}$ different?". This problem would be addressed both experimentally and theoretically in a near future.

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REFERENCES

- [1] R.R. Betts et al., Phys. Rev. Lett. **47**, 23(1981).
- [2] R.W. Zurmühle et al., Phys. Lett. **B129**, 384(1983).
- [3] P.H. Kutt et al., Phys. Lett **B155**, 384(1983).
- [4] A.H. Wuosmaa et al., Phys. Rev. **C36**, 1011(1987).
- [5] G. Leander et al., Nucl. Phys. **A239**, 93(1975),
M.E. Faber et al., Phys. Scr. **24**, 189(1981).
- [6] R.R. Betts et al., Proc. Inter. Conf. on Nuclear Physics,
Stony Brook, New York, 347(1983).
- [7] R.R. Betts et al., Phys. Lett. **B100**, 177(1981).
- [8] R.R. Betts et al., Phys. Rev. Lett. **46**, 313(1981).
- [9] R. Nouicer, Ph.D. Thesis, Strasbourg University, Report IReS 97-35.
- [10] R. Nouicer, C. Beck et al., Proc. of Int. Scho. Semi. on Heavy Ion Physics,
Dubna, Russia 1997, to be published, Report IReS 97-32, **nucl-ex/9711002** (1997)
- [11] C. Beck, R. Nouicer et al., Report IReS 97-22, **nucl-ex/9708004** (1997)
- [12] J. Randrup, Nucl. Phys. **A447**, 133(1985).
- [13] A.H. Wuosmaa et al. Phys. Rev. Lett. **58**, 1312(1987).
- [14] Y. Abe and E. Uegaki, private communications (1998).
- [15] E. Uegaki and Y. Abe, Phys. Lett. **B340**, 143(1994).
- [16] E. Uegaki and Y. Abe, Prog. Theor. Phys. **90**, 615(1993).
- [17] E. Uegaki and Y. Abe, Phys. Lett. **B231**, 28(1989)
- [18] D. Konnerth et al., Phys. Rev. Lett. **55**, 588(1985).
- [19] A. Gobbi and Nörenberg, in Heavy Ion Collisions,
Vol. 2, edited by R. Bock (North-Holland, Amsterdam, 1980), p128.

FIGURE CAPTIONS

Fig.1 : Excitation functions data for $^{28}\text{Si} + ^{28}\text{Si}$ scattering averaged over $67^\circ \leq \theta_{\text{c.m.}} \leq 95^\circ$ and for $^{24}\text{Mg} + ^{24}\text{Mg}$ scattering averaged over $66^\circ \leq \theta_{\text{c.m.}} \leq 93^\circ$.

Fig.2 : Potential energy surface for ^{56}Ni and for ^{48}Cr calculated in the Nilson-Strutinsky prescription. The β is the deformation parameter and the $M_r = M/56$ (or $M/48$) is the mass-asymmetry where M is the mass of the fragment in the exit-channel.

Fig.3 : Detection system used in the experiment $^{28}\text{Si} + ^{28}\text{Si}$.

- A) General view of Eurogam Phase II multi-detector array (gamma-ray detectors)
- B) inside view of the reaction chamber where four position-sensitive detectors (fragment detectors) can be observed.

Fig.4 : Two-dimensional energy spectrum E_4 versus E_3 of the fragments detected by one pair of position-sensitive Si detectors for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction.

Fig.5 : Mass spectra corresponding to the region 1.

- A) corresponds to the reaction products of $^{28}\text{Si} + ^{28}\text{Si}$.
- B) products arising from of the reaction ^{28}Si on the contamination ^{16}O .

The peaks have been identified by using γ -ray spectra.

Fig.6 : Ejectile energy E_3 versus excitation energy E_X two-dimensional plot of the $^{28}\text{Si} + ^{28}\text{Si}$ symmetric exit-channel..

Fig.7 : Experimental angular distributions of the elastic ($E_X \approx 0$ MeV), inelastic ($E_X \approx 1.7$ MeV) and mutual excitations ($E_X \approx 4, 6$ and 10 MeV) for the $^{28}\text{Si} + ^{28}\text{Si}$ symmetric exit-channel. The solid curves represent pure squared Legendre polynomial $[P_L(\cos \theta_{\text{c.m.}})]^2$ with $L = 38$.

Fig.8 : Experimental γ -ray angular correlations of the $(2_1^+, 2_1^+)$ states in the resonance region of the $^{28}\text{Si} + ^{28}\text{Si}$ exit channel for three quantization axes.

Fig.9 : Diagram illustrating the quantification axes $\vec{o}\vec{a}$, $\vec{o}\vec{b}$ and $\vec{o}\vec{c}$. The PSD 3 and 4 in coincidence are represented in the reaction plane. The spins directions are indicated according to experimental results as shown in Fig.8.

Fig.10 : Dinuclear configuration (oblate-oblate system) and the coordinates in the rotating molecular frame [9,15].

Fig.11 : Molecular model prediction for probability distributions of the $^{28}\text{Si} + ^{28}\text{Si}$ ($[2_1^+ \otimes 2_1^+]$ with $L = J - I$) system versus channel spin I .

Fig.12 : Molecular model prediction for Probability distributions of the $^{24}\text{Mg} + ^{24}\text{Mg}$ ($[2_1^+ \otimes 2_1^+]$ with $L = J - I$) system versus channel spin I .